CSE 331
Software Design & Implementation

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ADT Implementation: Representation Invariants

Specifying an ADT

Different types of methods:

1. **`creators`**
2. **`observers`**
3. **`producers`**
4. **`mutators`** (if mutable)

Described in terms of how they change the **abstract state**

- abstract description of what the object means
  - difficult (unless concept is already familiar) but vital
- specs have no information about concrete representation
  - leaves us free to change those in the future

Implementing a Data Abstraction (ADT)

To implement an ADT:

- select the representation of instances
- implement operations in terms of that representation

Choose a representation so that:

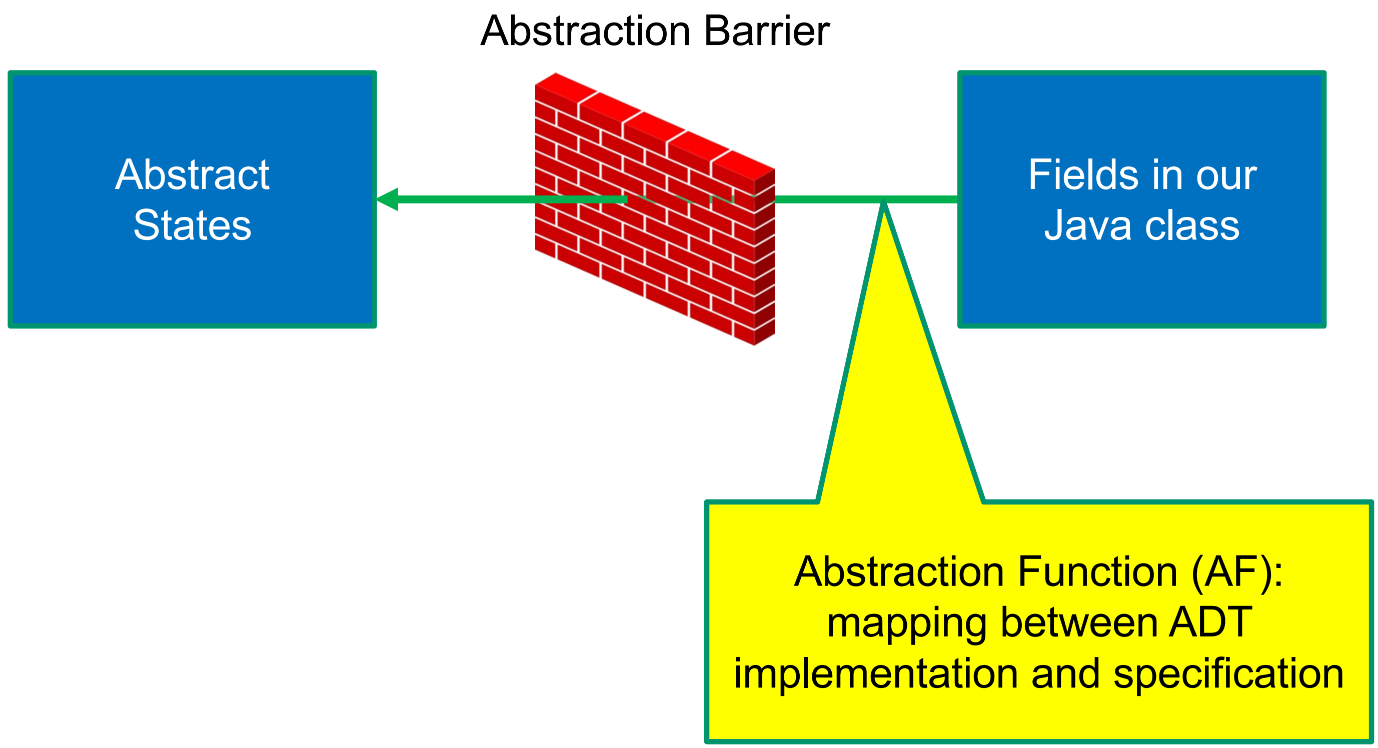
- it is possible to implement required operations
- the most frequently used operations are efficient / simple / …
  - abstraction allows the rep to change later
  - almost always better to start simple

Then use **reasoning** to verify the operations are correct

- two intellectual tools are helpful for this...

Data abstraction outline

ADT specification **ADT implementation**



Last time: abstraction function

- Allows us to check correctness
  - use reasoning to show that the method leaves the abstract state such that it satisfies the postcondition

```
// AF(this) = vals[0..len-1]
private int[] vals;
private int len;

// @requires length > 0
// @modifies this
// @effects this = this[0..length-2]
public void pop() { ... }
```

Last time: abstraction function

- Allows us to check correctness
  - use reasoning to show that the method leaves the abstract state such that it satisfies the postcondition

```
// AF(this) = vals[0..len-1]

// @requires length > 0
// @modifies this
// @effects this = this[0..length-2]
public void pop() {
```

{{ length > 0 }}

```
  len = len - 1;
```

{{ this = $this_{pre}$[0 .. $length_{pre}$ – 2] }}

```
}
```

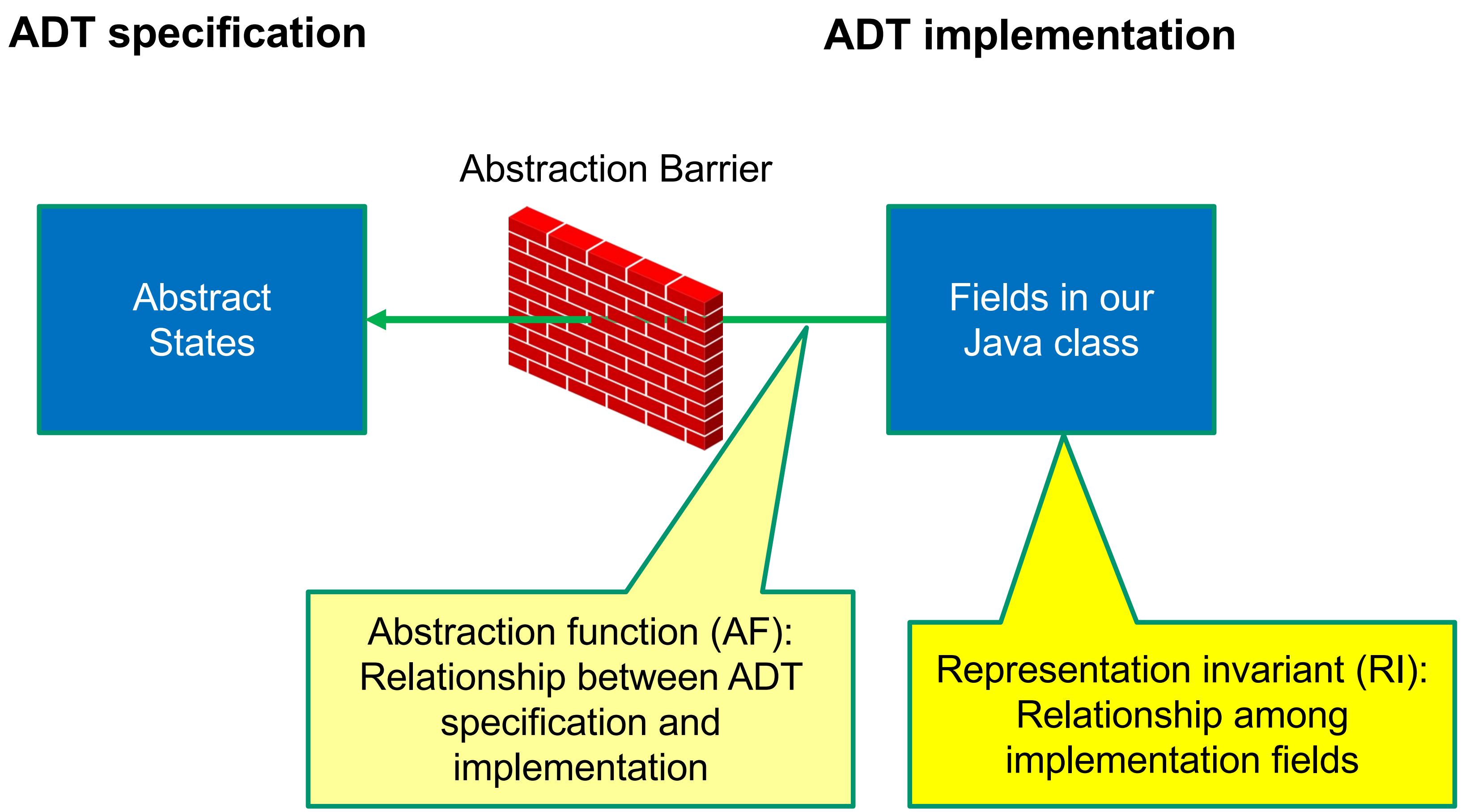
{{ len > 0 }}

{{ len = len_{pre} - 1 }}

⇒ {{ this = vals[0..len-1]

= vals[0..len_{pre}-2] }}

Data abstraction outline



Connecting implementations to specs

For implementers / debuggers / maintainers of the implementation:

Representation Invariant: maps Object → boolean

- defines the set of valid concrete values
- must hold before and after any public method is called
- **no object should *ever* violate the rep invariant**
  - such an object has no useful meaning

Abstraction Function: maps Object → abstract state

- says what the data structure *means* in vocabulary of the ADT
- **only defined** on objects meeting the rep invariant

Example: Circle

```
/** Represents a mutable circle in the plane. For example,
  * it can be a circle with center (0,0) and radius 1. */
public class Circle {

  // Rep invariant: center != null and rad > 0
  private Point center;
  private double rad;

  // Abstraction function:
  // AF(this) = a circle with center at this.center
  //   and radius this.rad

  //  ...
}
```

Example: Circle 2

```java
/** Represents a mutable circle in the plane. For example,
  * it can be a circle with center (0,0) and radius 1. */
public class Circle {

  // Rep invariant: center != null and edge != null
  //   and !center.equals(edge)
  private Point center, edge;

  // Abstraction function:
  // AF(this) = a circle with center at this.center
  //   and radius this.center.distanceTo(this.edge)

  //  ...
}
```

Example: Polynomial

```
/** An immutable polynomial with integer coefficients.
  * Examples include 0, 2x, and x + 3x^2 + 5x. */
public class IntPoly {

  // Rep invariant: coeffs != null
  private final int[] coeffs;

  // Abstraction function:
  // AF(this) = sum of this.coeffs[i] * x^i
  //   for i = 0 .. this.coeffs.length

  // ... coeff, degree, etc.
```

Example: Polynomial 2

```
/** An immutable polynomial with integer coefficients.
  * Examples include 0, 2x, and x + 3x^2 + 5x. */
public class IntPoly {

  // Rep invariant: terms != null and
  //     no two terms have the same degree and
  //     terms is sorted in descending order by degree
  private final LinkedList<IntTerm> terms;

  // Abstraction function:
  // AF(this) = sum of monomials in this.terms

  //  ... coeff, degree, etc.
```

Example: IntDeque

```
/** List that only allows insert/remove at ends. */
public class IntDeque {

  // RI: vals != null and 0 <= start < vals.length and
  //     0 <= len <= vals.length
  private int[] vals;
  private int start, len;

  // AF(this) =
  //   vals[start..start+len-1]      if start+len <= vals.length
  //   vals[start..] + vals[0..k]    otherwise
  // where k = start + len - vals.length.
```

Another example

```
class Account {
   private int balance;

   // history of all transactions
   private List<Transaction> transactions;
   …
}
```

Implementation-related constraints:

- Transactions ≠ null
- No nulls in transactions

Real-world constraints:

- Balance = Σ_i transactions.get(i).amount
- Balance ≥ 0

Defensive Programming with ADTs

Checking rep invariants

Should you write code to check that the rep invariant holds?

- Yes, if it's inexpensive [depends on the invariant]

- Yes, for debugging [even when it's expensive]

- Often hard to justify turning the checking off
  - better argument is removing clutter (improve understandability)

- Some private methods must not check

A great debugging technique:

Design your code to catch bugs by implementing and using a function to check the rep-invariant

Example: CharSet ADT

```
// Overview: A CharSet is a finite mutable set of Characters
// @effects: creates a fresh, empty CharSet
public CharSet() {…}

// @modifies: this
// @effects: this changed to this + {c}
public void insert(Character c) {…}

// @modifies: this
// @effects: this changed to this - {c}
public void delete(Character c) {…}

// @return: true iff c is in this set
public boolean member(Character c) {…}

// @return: cardinality of this set
public int size() {…}
```

Example: CharSet ADT

```
// Rep invariant: elts != null and
//        elts has no nulls and no dups
// AF(this) = list of chars in elts
private List<Character> elts;
```

Checking the rep invariant

Rule of thumb: check on entry *and* on exit (why?)

```
public void delete(Character c) {
  checkRep();
  elts.remove(c);  // removes 0 or 1 copies of c
  checkRep();
}


// Verify that elts contains no nulls or dups
private void checkRep() {
  for (int i = 0; i < elts.size(); i++) {
    assert elts.get(i) != null;
    assert elts.indexOf(elts.get(i)) == i;
  }
}
```

Practice *defensive programming*

- Question is not: will you make mistakes? You will.
- Question is: will you **catch** those mistakes before users do?

- Write and incorporate code designed to catch the errors you make
  - check rep invariant on entry and exit (of mutators)
  - check preconditions (don't trust other programmers)
  - check postconditions (don't trust yourself either)

- Checking the rep invariant helps *discover* errors while testing
- Reasoning about the rep invariant helps *discover* errors while coding

Practice *defensive programming*

- Checking pre- and post-conditions and rep invariants is one tip
- More of these in Effective Java
  - first required reading (see calendar for items)

- Focus on defensive programming against **subtle bugs**
  - obvious bugs (e.g., crashing every time) will be caught in testing
  - subtle bugs that only occasionally cause problems can sneak out
  - be especially defensive against (and scared of) these

Listing the elements of a CharSet

Consider adding the following method to **`CharSet`**

```
// returns: a List containing the members of this
public List<Character> getElts();
```

Consider this implementation:

```
public List<Character> getElts() { return elts; }
```

Does this implementation preserve the rep invariant?

Can't say!

Representation exposure

Consider this client code (outside the `CharSet` implementation):

```
CharSet s = new CharSet();
Character a = new Character('a');
s.insert(a);
s.getElts().add(a);
s.delete(a);
if (s.member(a)) …
```

- Representation exposure is external access to the rep
- Representation exposure is almost always **bad**
  - can cause bugs that will be **very hard to detect**
- Rule #1: Don't do it!
- Rule #2: If you do it, document it clearly and then feel guilty about it!

Avoiding representation exposure

- *Understand* what representation exposure is

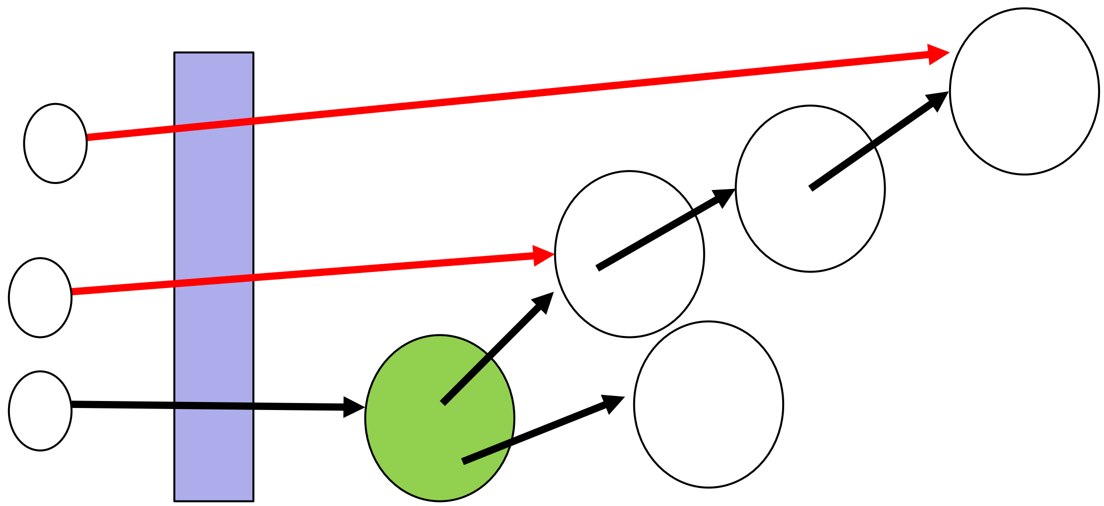
- *Design* ADT implementations to make sure it doesn't happen

- Treat rep exposure as a bug: *fix* your bugs
  - absolutely must avoid in libraries with many clients
  - can allow (but feel guilty) for code with few clients

- *Test* for it with *adversarial clients:*
  - pass values to methods and then mutate them
  - mutate values returned from methods

`private` is not enough

- Making fields **`private`** does *not* suffice to prevent rep exposure
  - see our example
  - issue is ***aliasing of mutable data outside the abstraction***



- So **`private`** is a hint to you: no aliases outside abstraction to references to mutable data reachable from **`private`** fields
- Three general ways to avoid representation exposure…

Avoiding rep exposure (way #1)

- One way to avoid rep exposure is to make copies of all data that cross the abstraction barrier
  - Copy in [parameters that become part of the implementation]
  - Copy out [results that are part of the implementation]
- Examples of copying (assume **`Point`** is a mutable ADT):

```
class Line {
    private Point s, e;
    public Line(Point s, Point e) {
        this.s = new Point(s.x,s.y);
        this.e = new Point(e.x,e.y);
    }
    public Point getStart() {
        return new Point(this.s.x,this.s.y);
    }
    …
```

Avoiding rep exposure (way #2)

- One way to avoid rep exposure is to exploit the immutability of (other) ADTs the implementation uses
  - aliasing is no problem if nobody can change data
    - have to mutate the rep to break the rep invariant
- Examples (assuming **`Point`** is an *immutable* ADT):

```
class Line {
    private Point s, e;
    public Line(Point s, Point e) {
        this.s = s;
        this.e = e;
    }
    public Point getStart() {
        return this.s;
    }
    …
```

Alternative #3

```
// returns: elts currently in the set
public List<Character> getElts() { // version 1
  return new ArrayList<Character>(elts);//copy out!
}

public List<Character> getElts() { // version 2
  return Collections.unmodifiableList(elts);
}
```

From the JavaDoc for **`Collections.unmodifiableList`**:

Returns an unmodifiable view of the specified list. This method allows modules to provide users with "read-only" access to internal lists. Query operations on the returned list "read through" to the specified list, and attempts to modify the returned list… result in an **`UnsupportedOperationException`**.

The good news

```
public List<Character> getElts() { // version 2
  return Collections.unmodifiableList(elts);
}
```

- Clients cannot *modify (mutate)* the rep
  - cannot break the rep invariant
- (For long lists,) more efficient than copy out
- Uses standard libraries

The bad news

```
public List<Character> getElts() { // version 1
 return new ArrayList<Character>(elts);//copy out!
}
```

```
public List<Character> getElts() { // version 2
 return Collections.unmodifiableList(elts);
}
```

The two implementations do not do the same thing!

- both avoid allowing clients to break the rep invariant
- both return a list containing the elements

But consider:

```
xs = s.getElts();
s.insert('a');
xs.contains('a');
```

Version 2 is *observing* an exposed rep, leading to different behavior

Different specifications

Ambiguity of "returns a list containing the current set elements"

"returns a fresh mutable list containing the elements in the set *at the time of the call*"

versus

"returns read-only access to a list that the ADT *continues to update to hold the current elements in the set*"

A third spec weaker than both [but less simple and useful!]

"returns a list containing the current set elements. *Behavior is unspecified (!) if* client attempts to mutate the list or to access the list after the set's elements are changed"

Also note: Version 2's spec also makes changing the rep later harder

– only "simple" to implement with rep as a **`List`**

Suggestions

Best options for implementing `getElts()`

- if O(n) time is acceptable for relevant use cases, copy the list
  - safest option
  - best option for changeability
- if O(1) time is required, then return an unmodifiable list
  - prevents breaking rep invariant
  - clearly document that behavior is unspecified after mutation
  - ideally, write a your own unmodifiable view of the list that throws an exception on all operations after mutation
- if O(1) time is required and there is no unmodifiable version and you don't have time to write one, expose rep and feel guilty